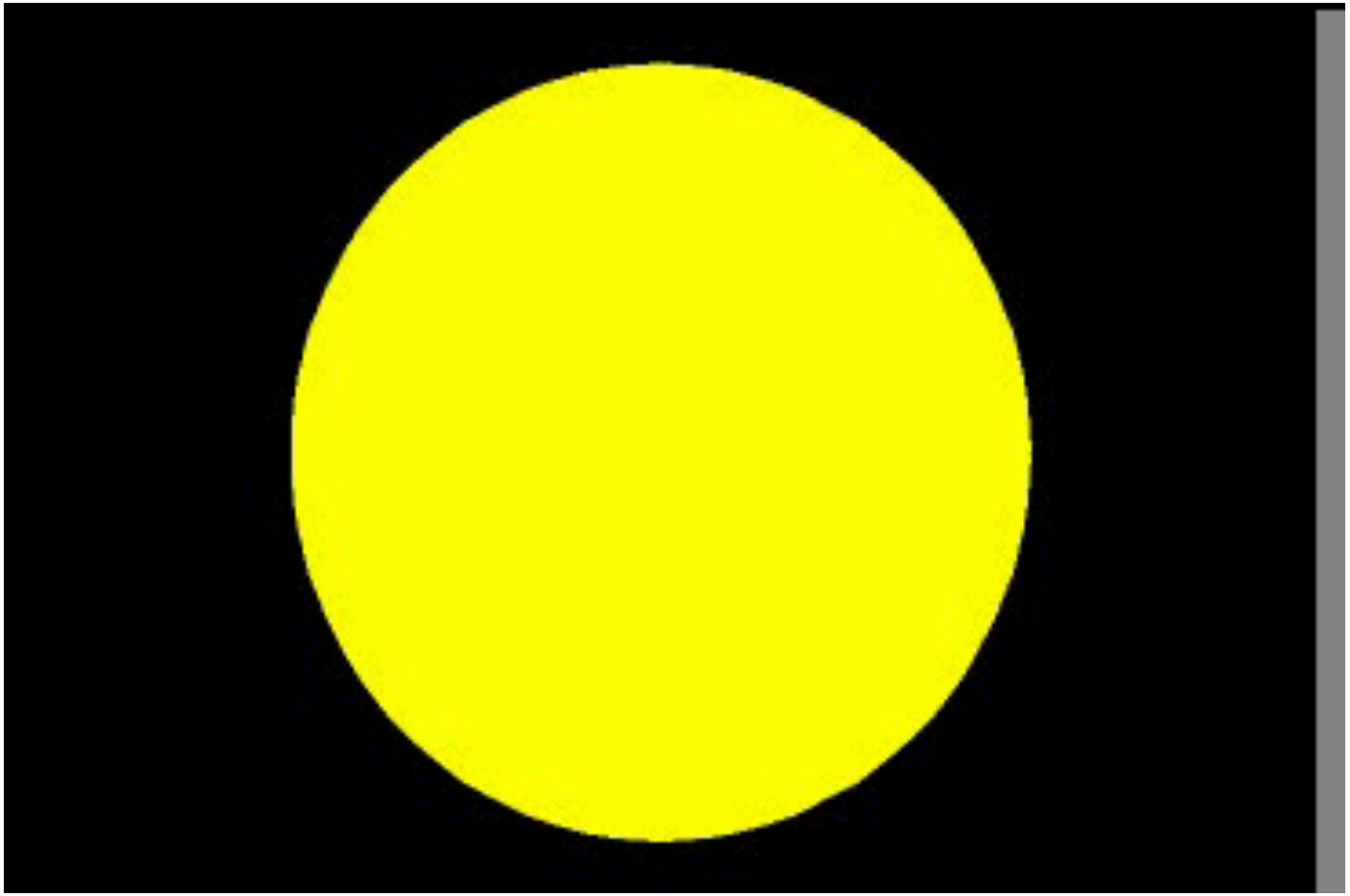
Subsurface Flow Maps for Modeling Magnetic Flux Transport and Evolution of Active Regions

Alexander Kosovichev and Junwei Zhao
New Jersey Institute of Technology
Stanford University

Motivation

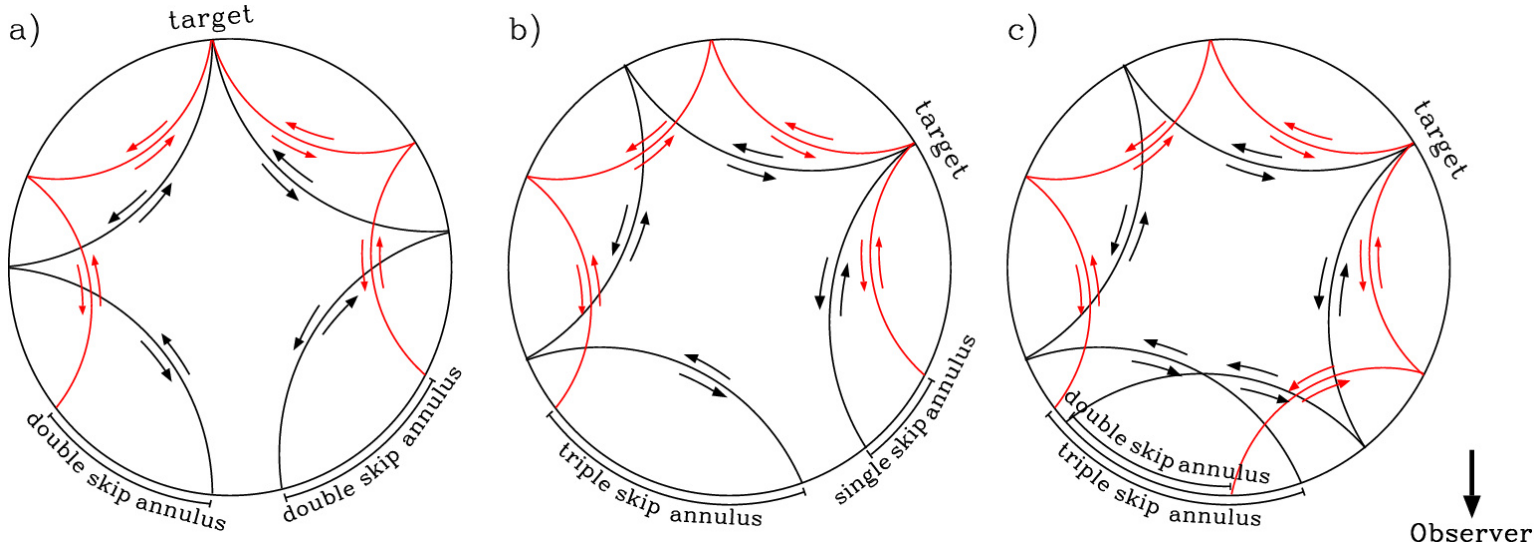
- The solar magnetic activity is generated and controlled by plasma flows beneath the visible surface of the Sun.
- For physics-based space weather forecasts it is critical to probe the subsurface dynamics on various temporal scales, from hours to the solar cycles.
- Helioseismology provides a capability to observe the subsurface flows,
- The subsurface flow maps represent the Solar Subsurface Weather, and can be used for space weather forecasts from flare events to the solar cycle.

Methodology:
Time-distance helioseismology
- solar acoustic tomography



3D sound-speed variations and the flow velocity are determined from the observed acoustic travel times by applying a multi-channel deconvolution technique.

Far-side measurement schemes



4-skip: 2×2
6-skip: 3×3
8-skip: 4×4

4-skip: 1×3
8-skip: 2×6

5-skip:
2×3

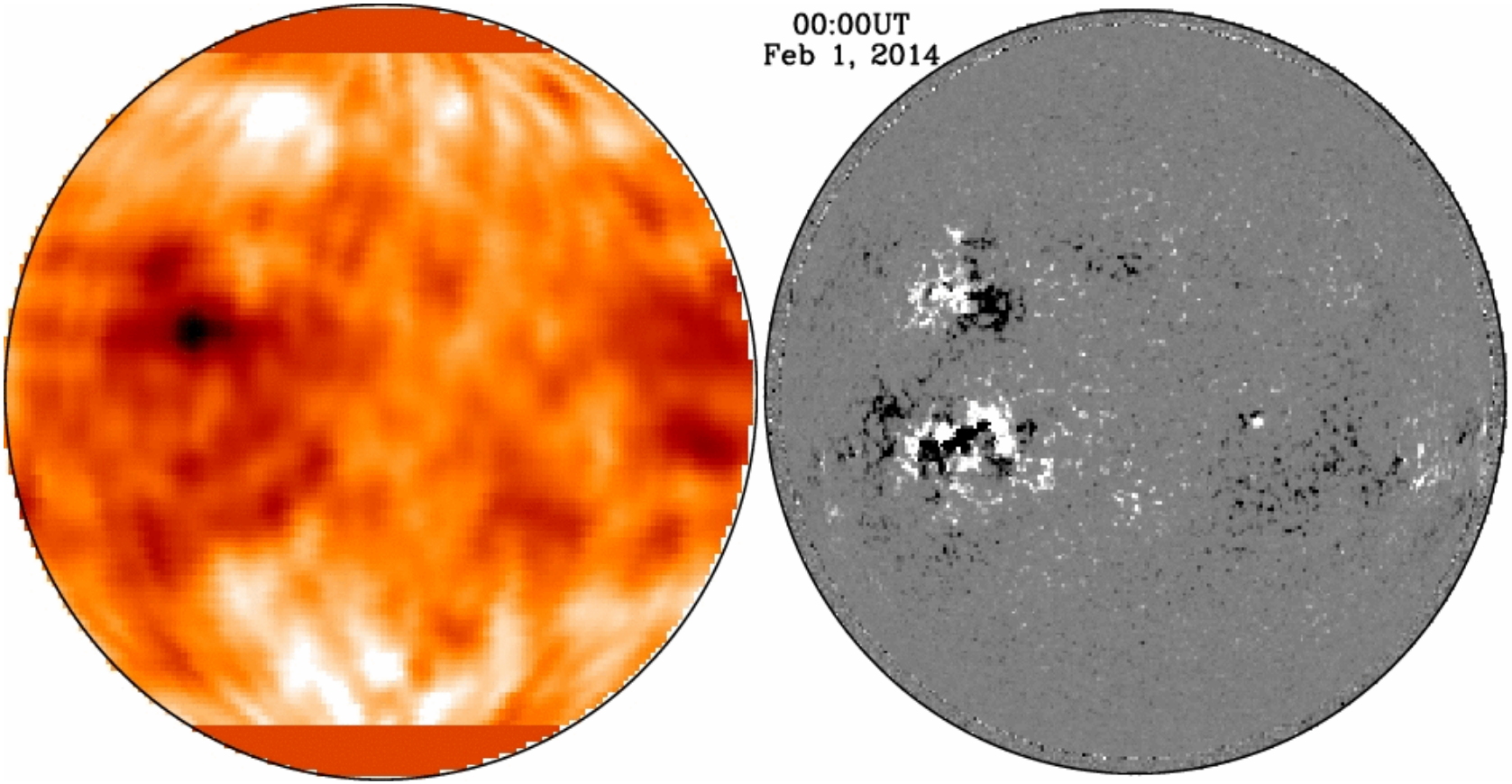
3-skip: 1×2
6-skip: 2×4

Our new far-side maps are a combination of these 14 sets of far-side maps from different schemes.

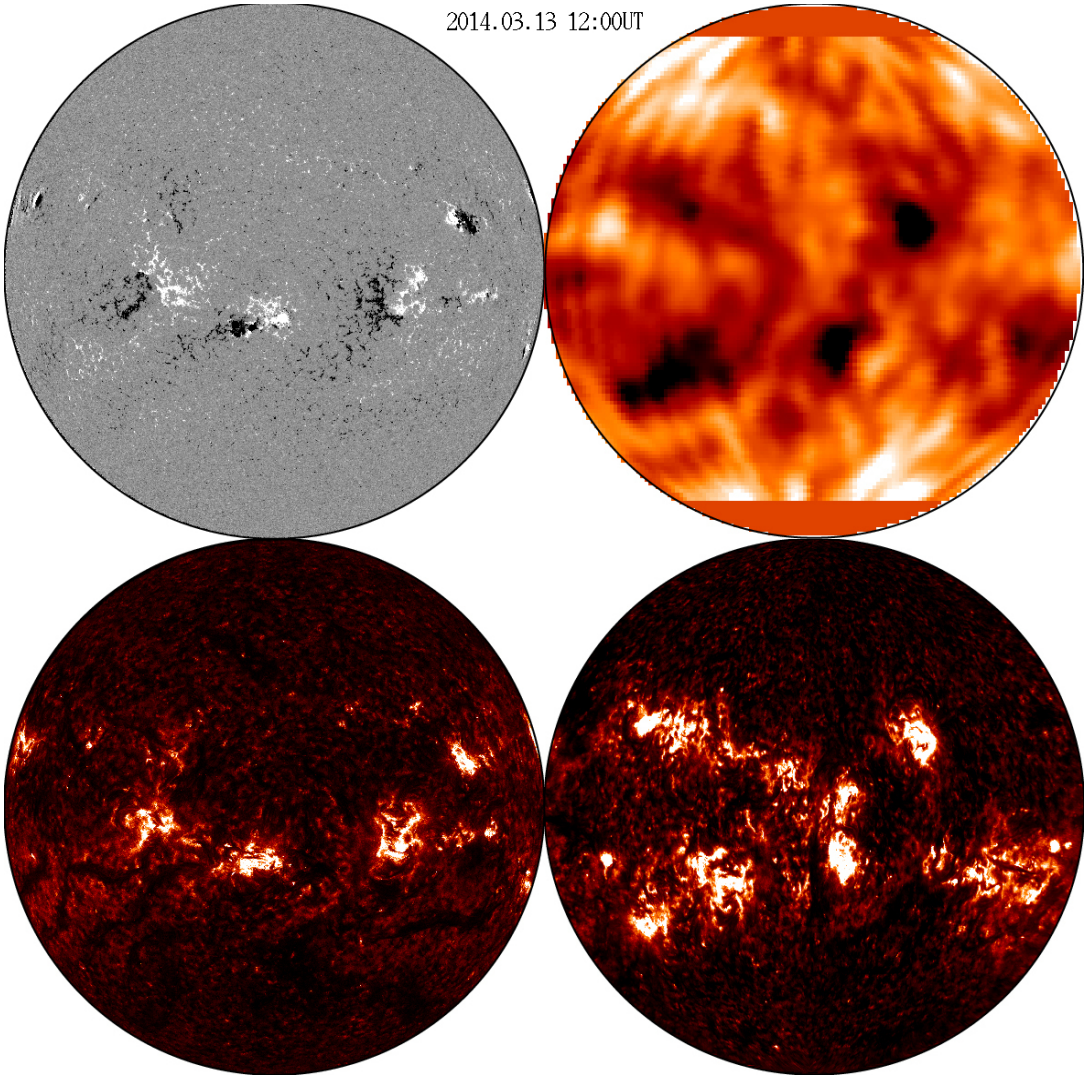
Prediction of magnetic field distribution on the far-side of the Sun

far-side travel-time shifts

near-side magnetic field



We are able to establish a relationship between the helioseismic signals and the STEREO 304Å images, and thus convert the helioseismic images into far-side magnetograms.



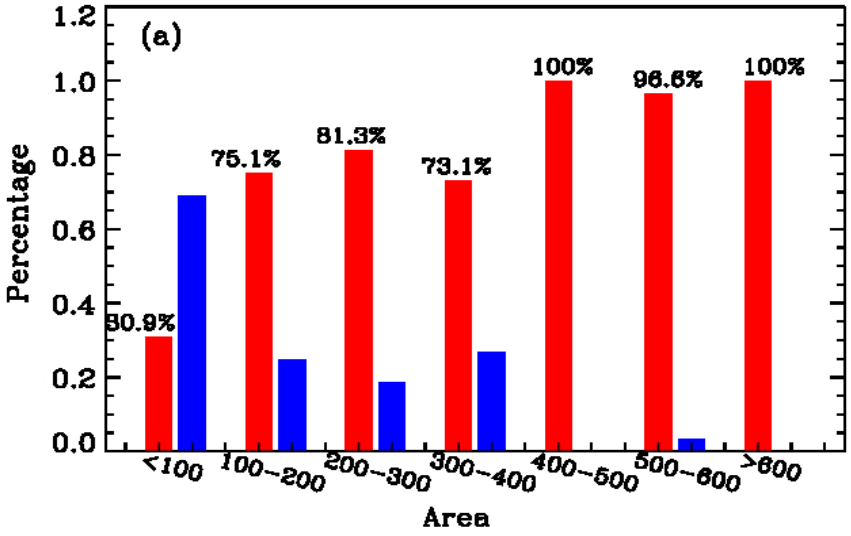
HMI near-side magnetogram

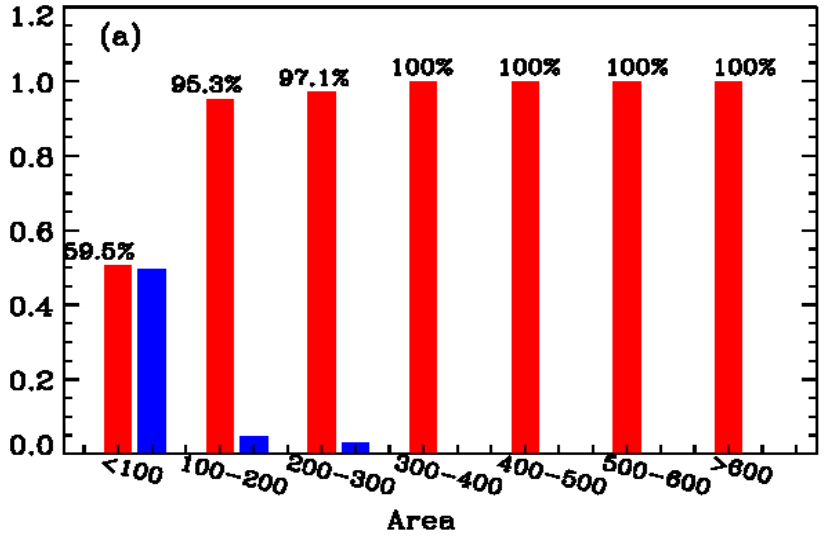
Time-distance far-side image

AIA near-side 304Å image

STEREO far-side 304Å image

Success Rate of Detection of Far-Side Active Regions

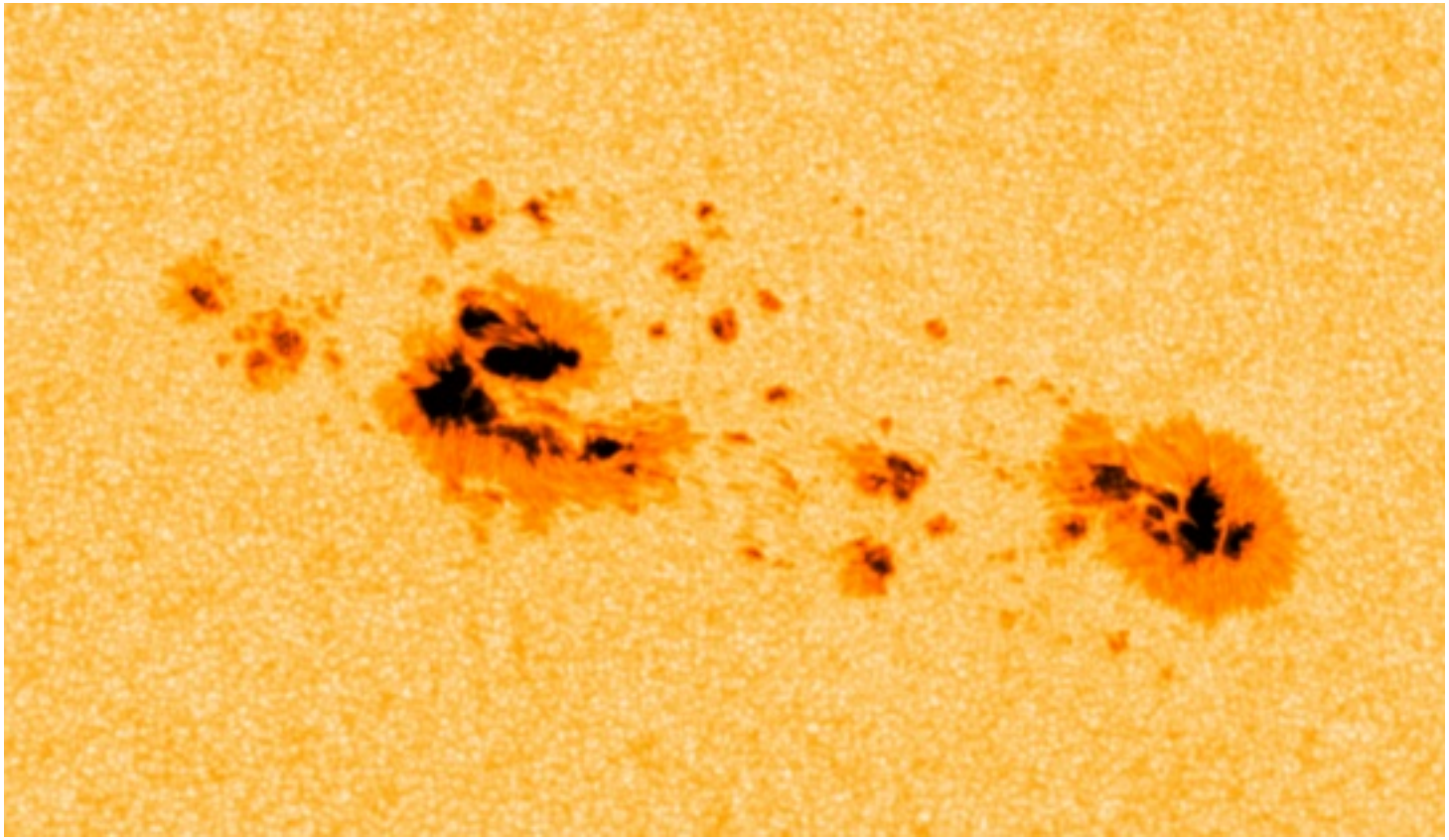




Based on 3 month statistics (Jan 1 – Mar 31, 2014), it is found that for active regions larger than 400 units (1 unit = 1.4 μ hemisphere), they are nearly 100% detectable in helioseismic images. For active regions between 100 and 400 units, 75% of them are detectable in helioseismic images.

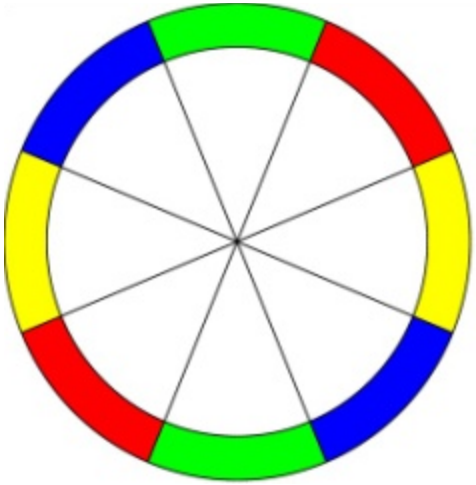
For helioseismic far-side active regions with an area larger than 100 units, they nearly 100% correspond to a STEREO far-side active region.

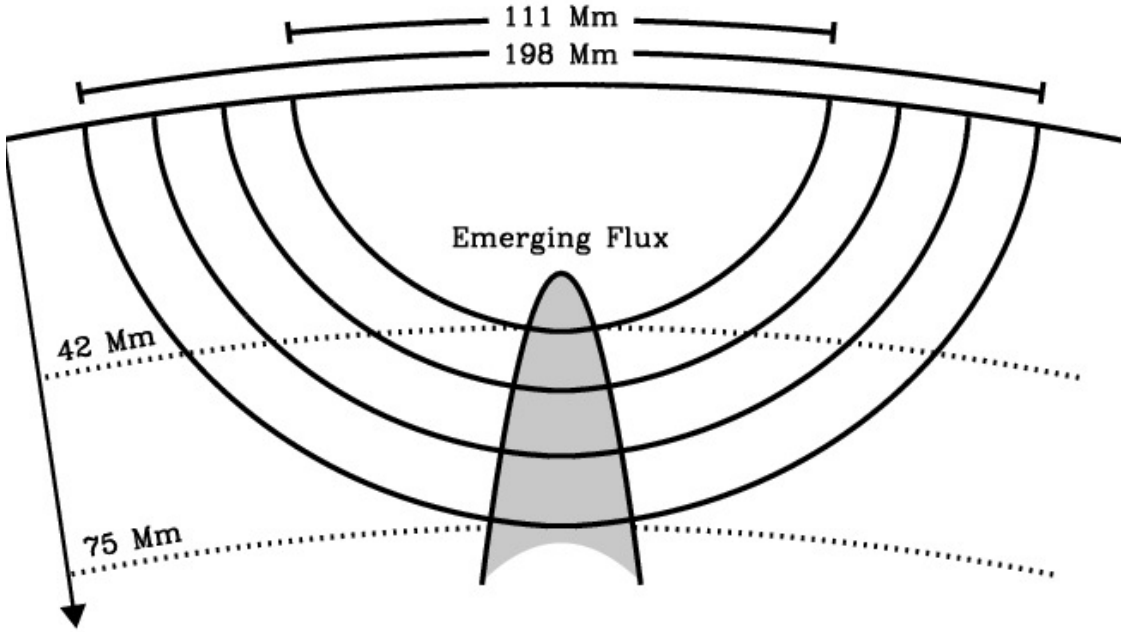
Case study: NOAA 11726 – helioseismic diagnostics of the largest emerging active region observed by HMI



Helioseismology method of detection of emerging magnetic flux inside the Sun

Deep-focus Time-Distance Helioseismology: solar oscillation signal is filtered to select acoustic waves traveling to depth 40-70 Mm (right), averaged over arcs (left), and cross-correlated for opposite arcs.
Travel-time perturbations are measured by fitting Gabor wavelet. This method has been tested with 3 different instruments (MDI, HMI, GONG) for many quiet and emerging flux regions.



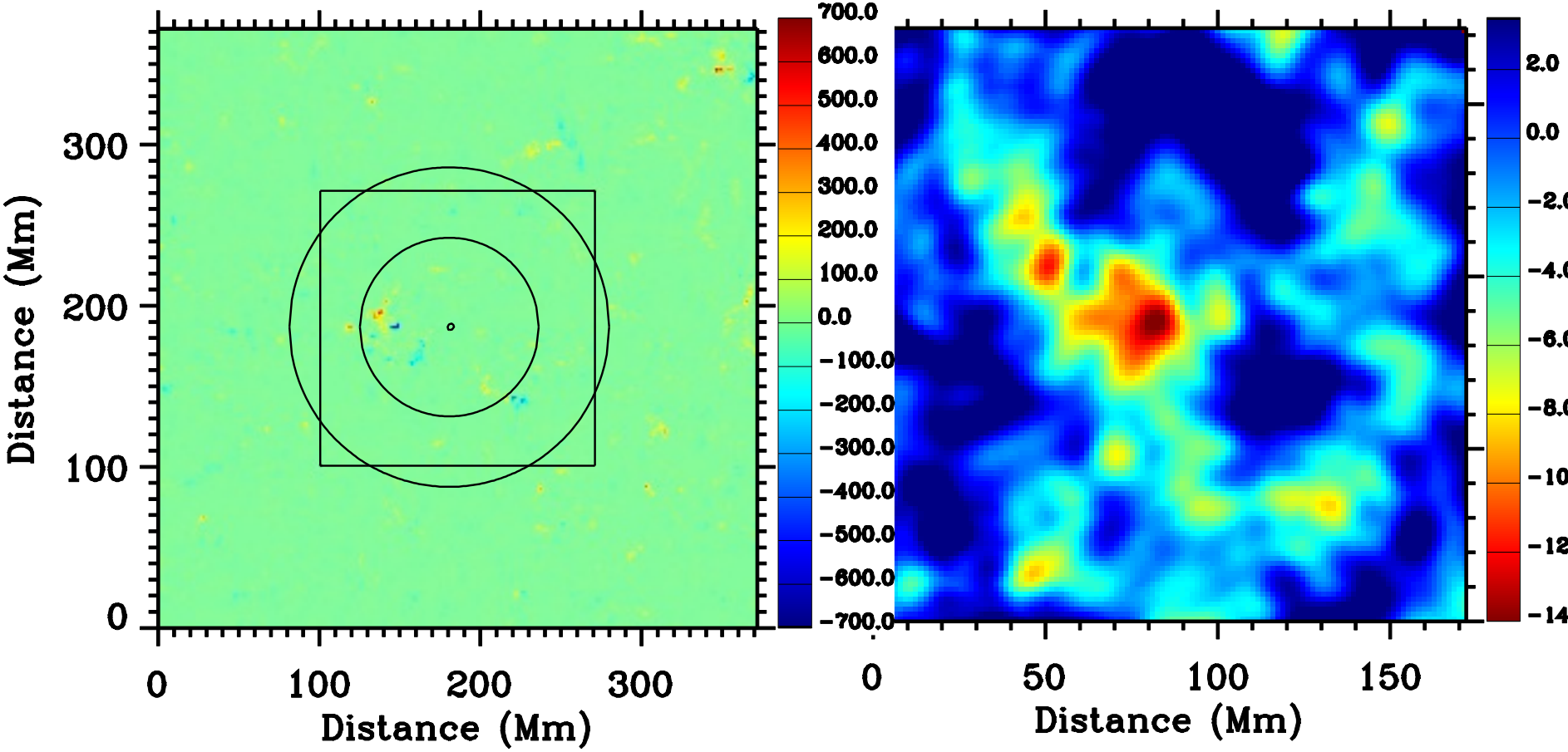


Ilonidis, Zhao, Kosovichev, 2011

Illustration of detection of emerging flux

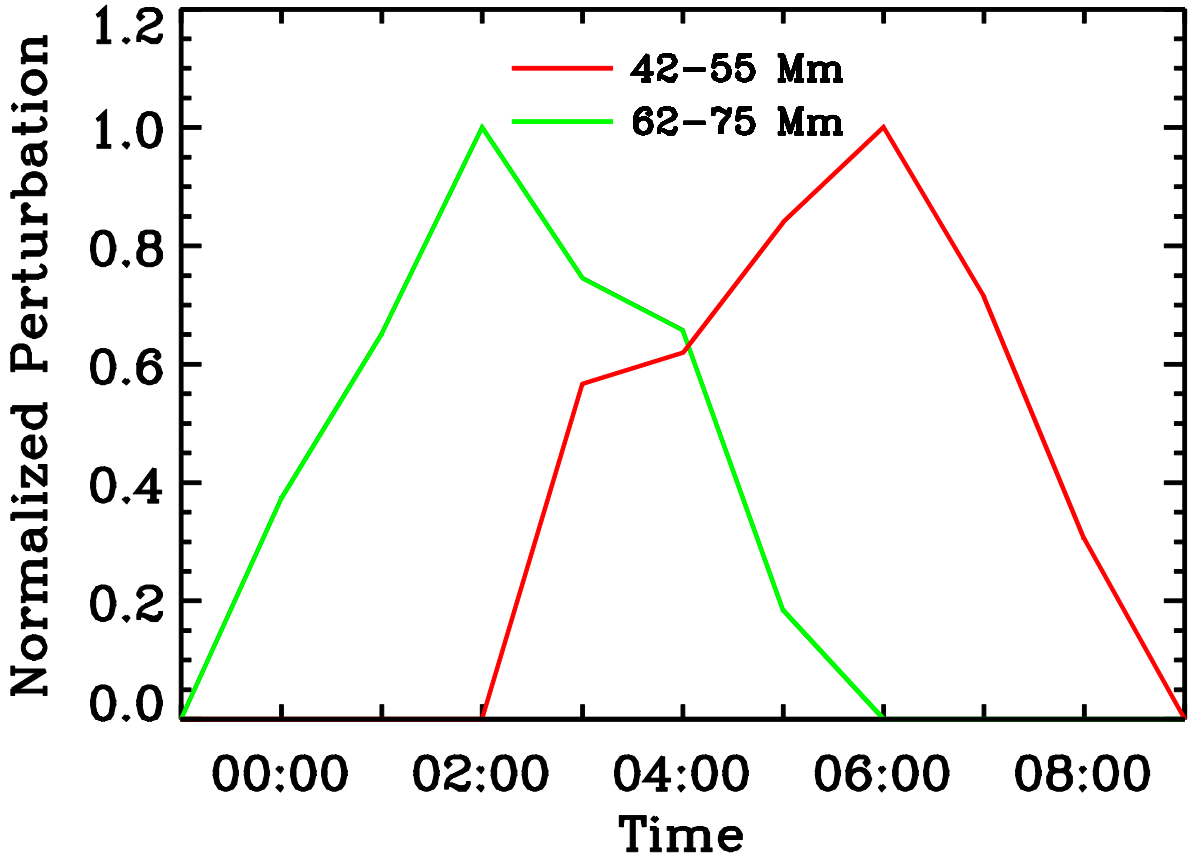
Detection of the deep structure prior the emergence of AR NOAA 11726

(April 19, 2013, 3:00 UT)

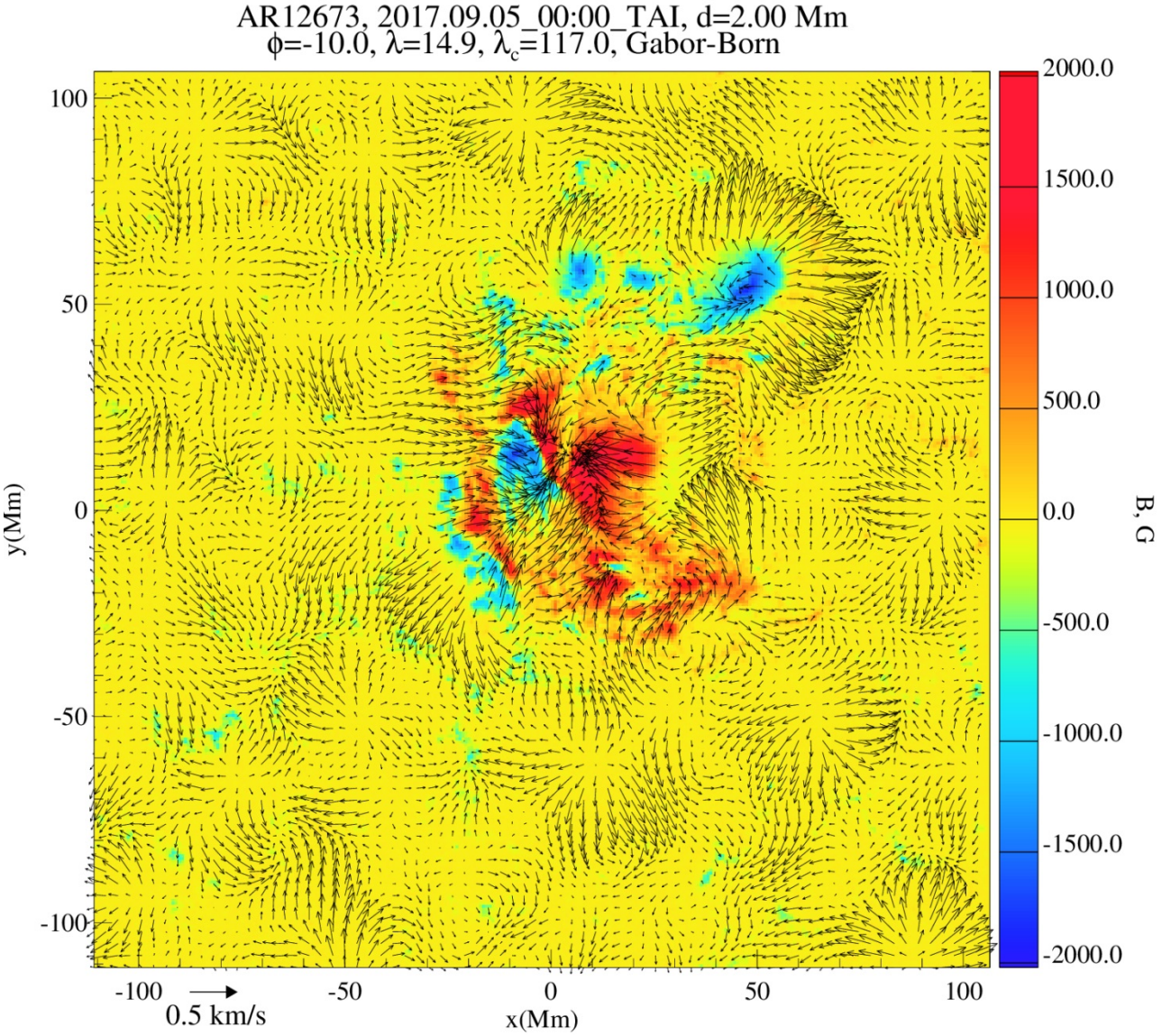


(Ilonidis, et al. 2015)

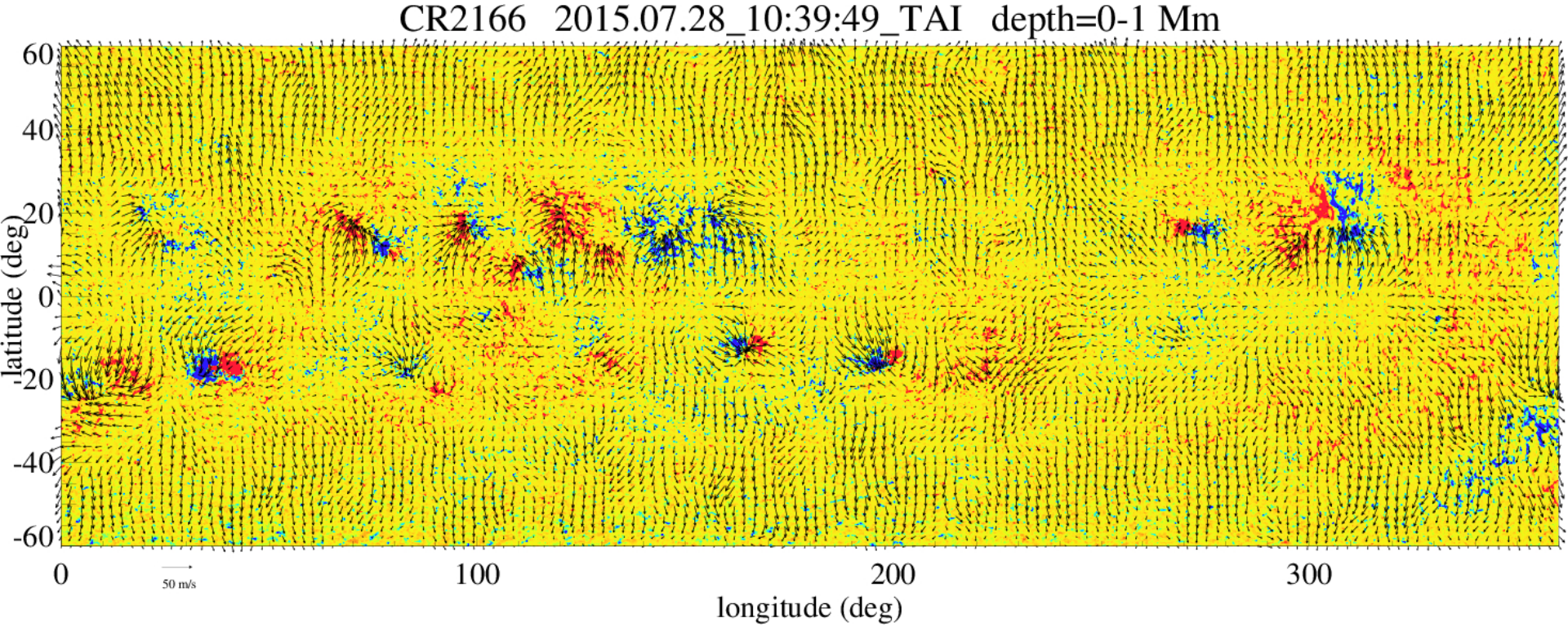
Evolution of the deep structure of AR11726 (time after 00:00 UT, April 19, 2013)



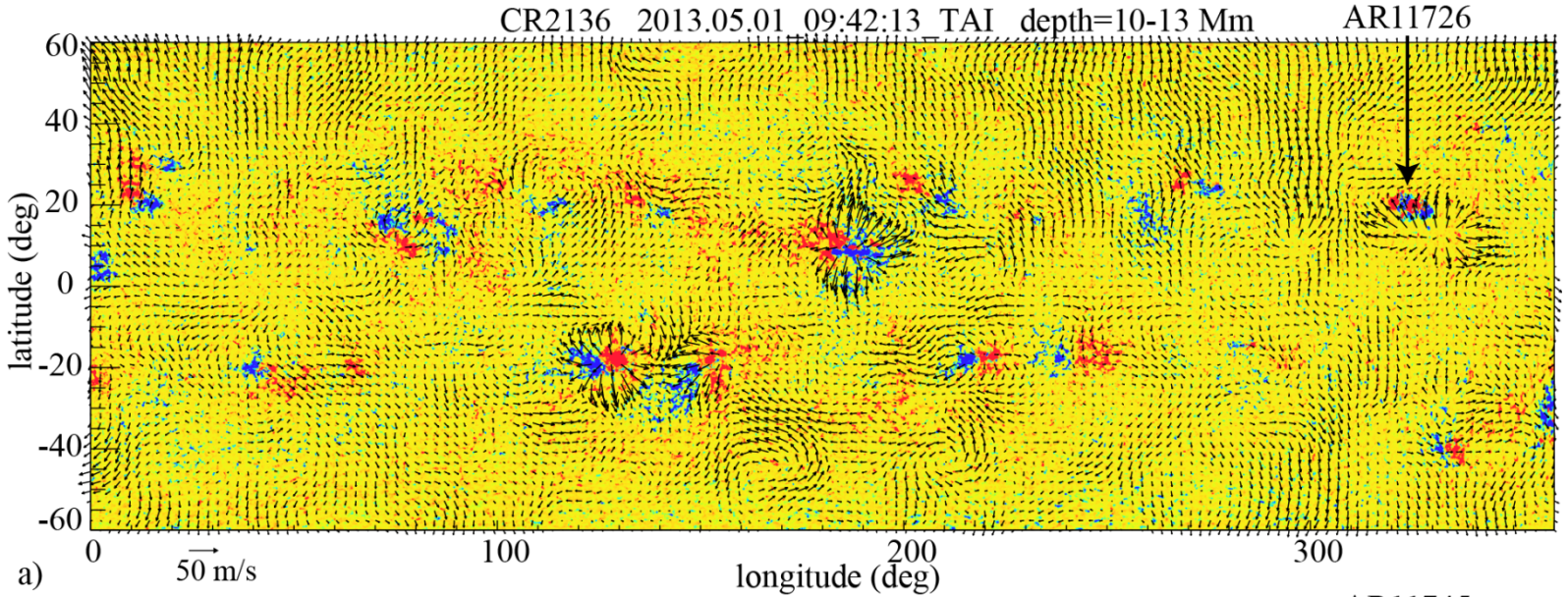
Strong converging flows around the polarity inversion lines are observed prior major flares

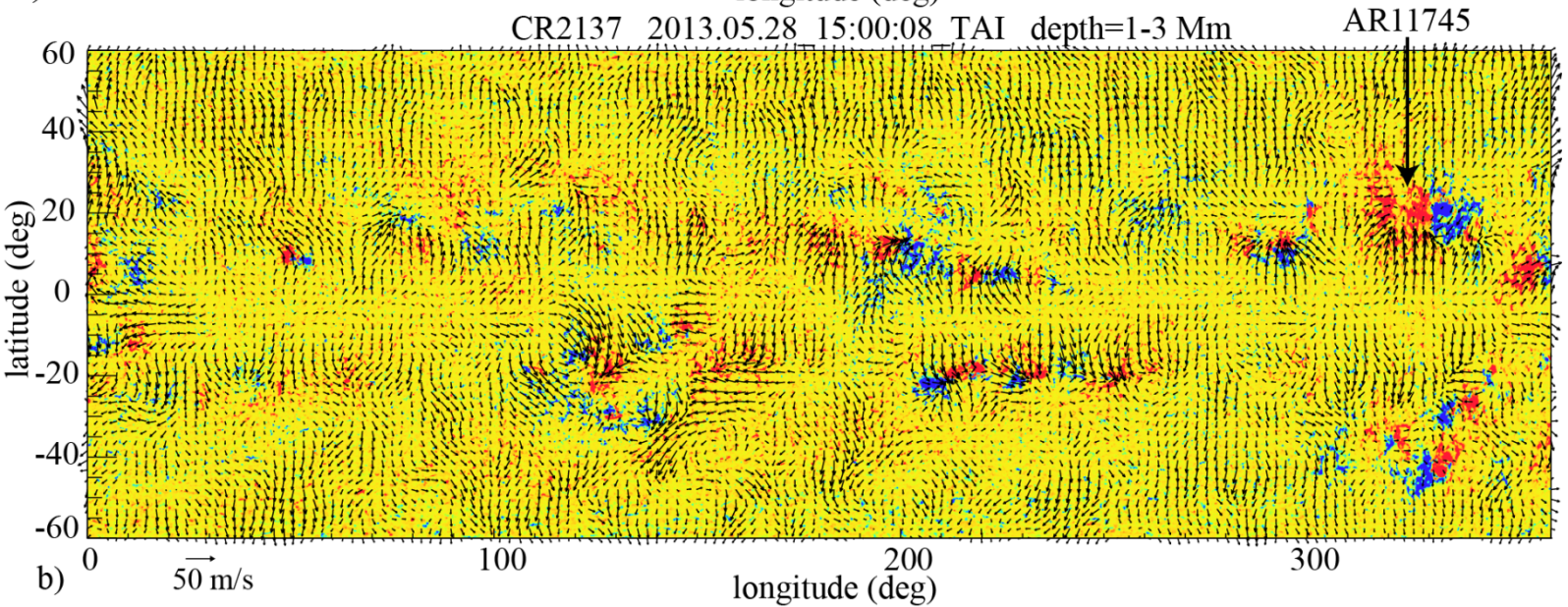


Synoptic flow maps:
Solar Subsurface Weather



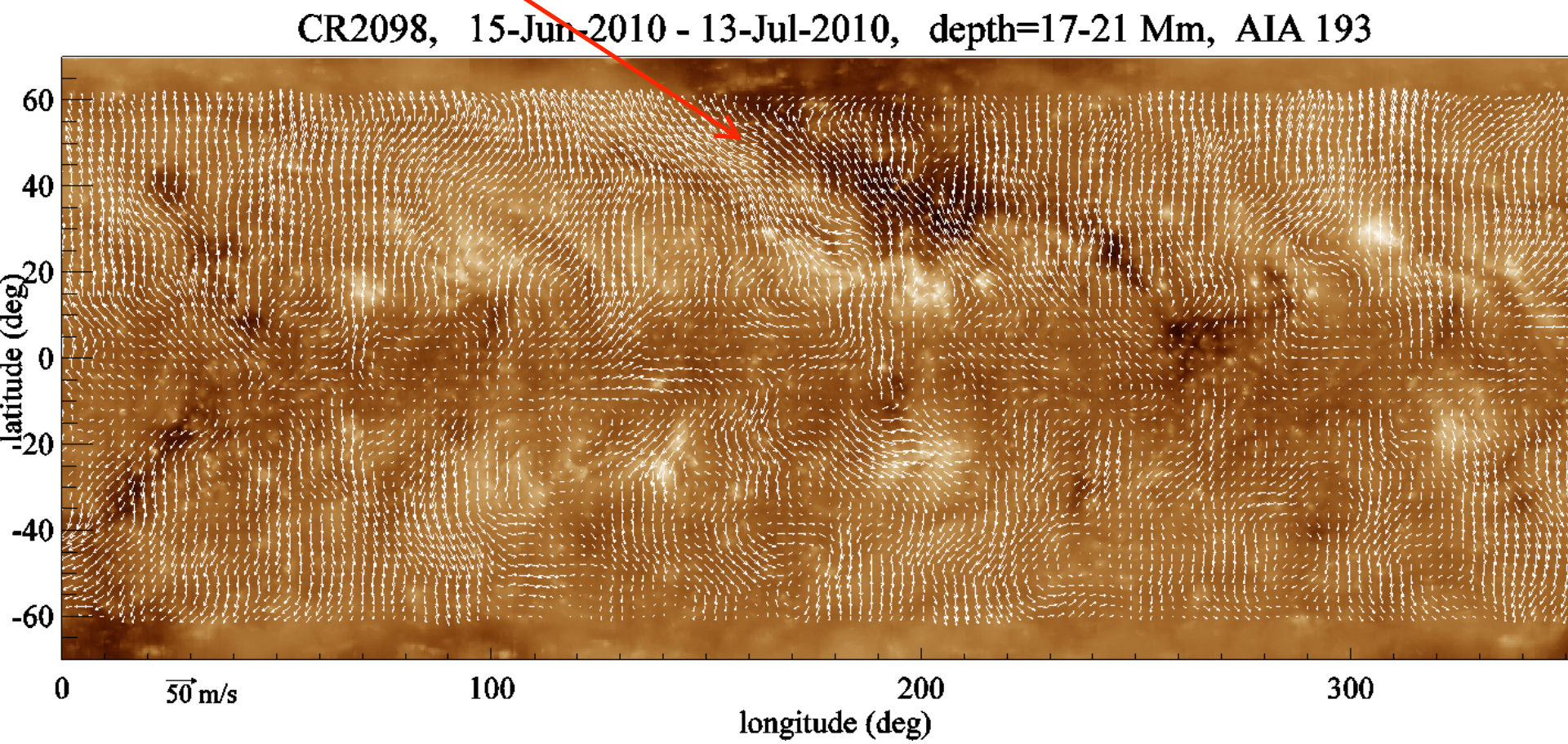
Solar Subsurface Weather: prediction of development of active regions





Links between the subsurface dynamics and the large-scale structure of the corona

Large-scale stable flow patterns are associated with coronal holes.

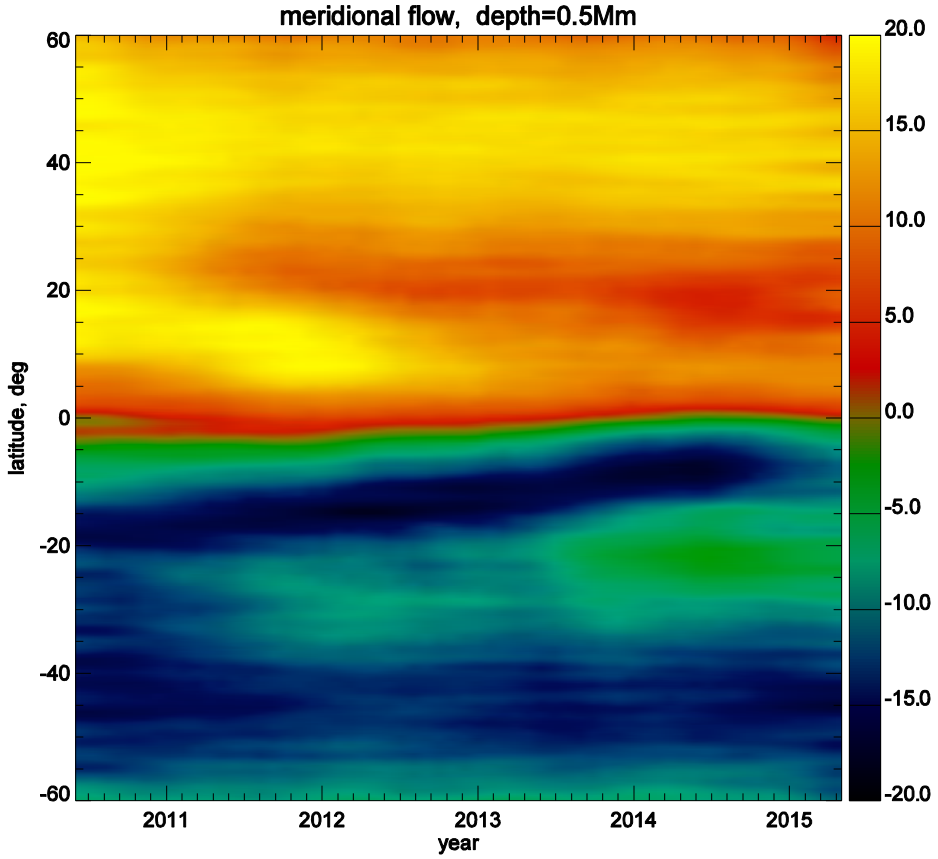


Solar-Cycle Variations of Zonal and Meridional Flows Affect the Magnetic Flux Transport

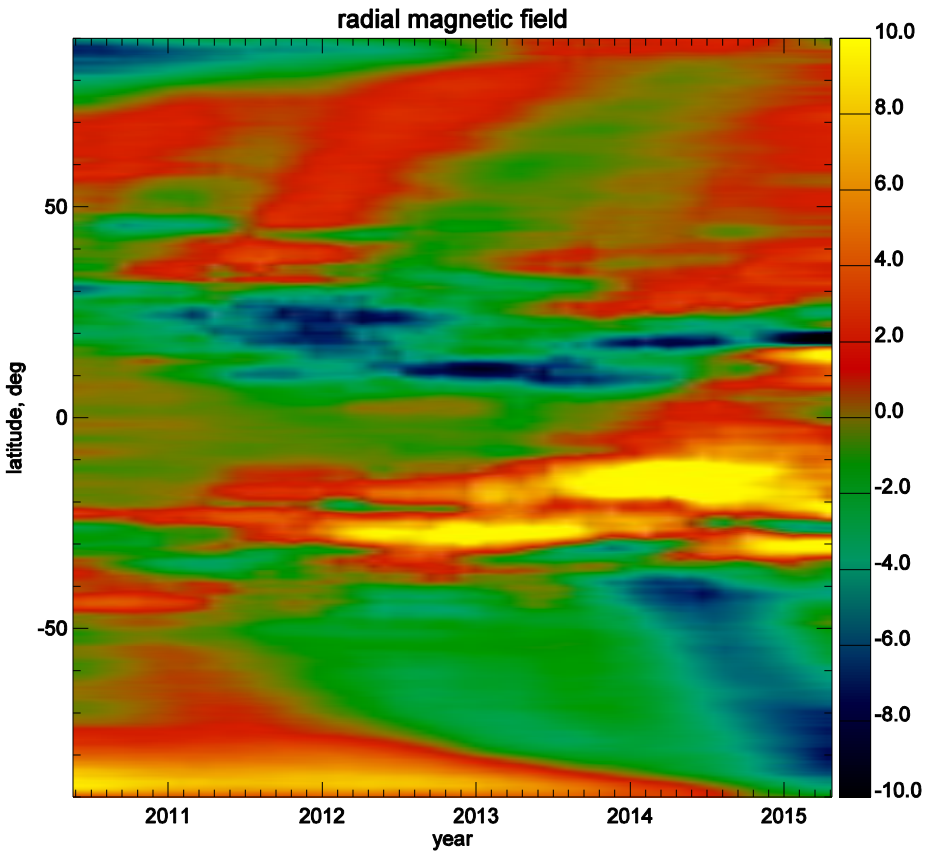
- Calculate monthly averages of the latitudinal and longitudinal flow components
- Calculate time-latitude diagrams
- Smooth with a 1-year running window to remove the B-angle variations

Variations of the meridional flows in 2010-15 show significant North-South asymmetry correlated with the magnetic field evolution

Meridional flow



Magnetic butterfly diagram



Summary of progress

- Data from the Helioseismic and Magnetic Imager on Solar Dynamics Observatory are used for producing uninterrupted high-resolution full-disk subsurface flow maps.
- The results reveal:
  - The subsurface dynamics of emerging and developing active regions, including emergence on the far-side of the Sun
  - Solar-cycle variations of large-scale and meridional flows.
  - Links between the active regions dynamics and the solar-cycle variations.
- The flow maps are available on-line from the Joint Science Operations Center (JSOC) at Stanford, and should be used for input into the CCMC models.